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**SIMULATION VALIDATION FOR AN  
AUTOMATIC AIR COLLISION  
AVOIDANCE SYSTEM IN PREPARING  
FOR FLIGHT TEST**



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# **SIMULATION VALIDATION FOR AN AUTOMATIC AIR COLLISION AVOIDANCE SYSTEM IN PREPARING FOR FLIGHT TEST**

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**Keywords:** Collision Avoidance, Escape Maneuver, Nuisance Free, Failure Safe Operation

## **Abstract**

This paper presents performance evaluation of an algorithm for an Automatic Air Collision Avoidance System (Auto ACAS or simply ACAS) that has been developed by the U.S. Air Force and its Swedish counter part, Forsvaret Materielverk (FMV). The algorithm uses the optimal coordinated escape maneuvers to avoid mid-air collision, while satisfying the imposed system requirements. In addition, the algorithm can simultaneously accommodate multiple aircraft in a collision course by activating the coordinated escape maneuvers. It also allows close formation flight and rejoin without activating the escape maneuver when certain conditions are met. The algorithm uses GPS and Navigational System for the universal time and position information. This information is exchanged through a data link between the in-network neighboring aircraft to detect collision potentials, select the optimal escape maneuver, and execute the optimal escape maneuver when the collision becomes imminent. The algorithm has its own integrity management system to operate safely against failures and GPS / data link dropout. The functionality of the algorithm has been tested through layers of simulation evaluation with flight simulators. With the improvements made based on pilots' comments who flew the simulator, the algorithm is now nearly ready for flight test.

## **Introduction**

The current trend of aviation is to launch many uninhabited air vehicles (UAVs) in the near future in order to relieve pilots from high-risk missions. However, this forces manned aircraft to share the same airspace with UAVs. Therefore, safety issues, particularly, those with respect to mid-air collision avoidance become critical. The Swedish AF recently had an incident where the flight lead was almost hit by his wingman during air-to-air combat training. To resolve these problems, the United State Air Force Research Laboratory, The Boeing Company, Lockheed Martin, NASA, FMV and Saab are jointly developing the Automatic Air Collision Avoidance System.

For manned systems, there are several air collision avoidance systems, which alert collisions potential to pilots at distance of several miles. All of these systems require pilot action to avoid the collision. Unlike this man-in-the-loop collision avoidance system, the method presented in the current paper does not require pilot's input. In other words, the system is completely automatic, and carries out all the tasks from collision detection to execution of escape maneuver without pilots' action. This allows the pilot to focus only on his mission. Discussion on the earlier development of this system can be found in [1], [2].

In addition to designing a system that detects collision potential and executes the optimal escape maneuver, a system needs to be designed that also satisfies certain requirements. One such requirement used as a design guideline is nuisance free operation. Major contributing elements to nuisance warning are: 1) the escape maneuver and its initiation and termination, 2) return of control to the pilot, 3) uncertainty and data latency, 4) audio and visual cues, 5) the rules of the road and 6) the escape maneuver prediction algorithm. Discussion on how each of these elements predictably contributes to the nuisance warnings can be found in [3].

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In the following sections, a brief discussion on the current state of the algorithm architecture is explained. Then a discussion on intruder data reconstruction follows. After the optimal escape maneuver selection is discussed, conditions on escape maneuver activation and termination are also discussed. Finally, the results from the simulation evaluation are discussed, and the findings are summarized.

### **1. Algorithm Architecture**

As soon as the data is received through data link, the algorithm first reconstructs the escape trajectories of neighboring aircraft (called intruders as opposed to the own aircraft called host). Then the algorithm checks the validity of the data. The algorithm performs data deadreckoning on both the intruder and host positions to line up with the same reference time. The algorithm looks at all intruders in the neighborhood and selects threats at each time instance. In the collision detection module, the algorithm predicts the minimum separation distance based on the selected escape maneuver. If the predicted minimum separation distance is converging to a predetermined safety distance, the algorithm will initiate the escape maneuver to avoid collisions. Otherwise, it holds the selected escape maneuver, and goes through another round of optimization process to update the escape maneuver. The resulting escape maneuver will be sent to other aircraft through the data link.

### **2. Intruder Data Reconstruction**

In order to minimize the size of the data package being sent through the data link, a few points on the aircraft escape trajectory are sent by the data link. The algorithm needs to reconstruct the intruder's escape trajectory. Based on the possible escape angles, escape trajectories with the maximum allowable roll rate and the maximum allowable g's are simultaneously calculated.

### **3. Optimal Coordinated Escape Maneuvers**

In order to select the best escape maneuver for multiple intruders, the algorithm first calculates the estimated minimum separation distance between the host and each intruder. This is done by curve fitting both the intruder and host flight path as a function of time, and by finding the analytic solution for the minimum separation distance between two flight paths.

Since each approximated flight path is represented by a polynomial function in time, the necessary condition for optimality is applied to a norm of relative position

$$d/dt ||\text{Relative Position as a function of time}|| = 0$$

This yields time instance  $T_{min}$  at which the minimum separation distance occurs.

To find the best combination of escape maneuvers between the host and intruders, the minimum separation distance for each possible combination of escape maneuvers is first calculated. Among all the possible maneuver combinations, the one that attains the largest minimum separation distances is selected as the optimal combination of the escape maneuvers.

### **4. Escape Maneuver Activation and Termination**

The escape maneuver determined via the optimization process is activated when the predicted minimum separation distance becomes smaller than the predetermined minimum safety distance (see [1] for more details). The escape maneuver is terminated when the separation distance starts increasing, i.e., when the minimum separation has been reached.

### **5. Simulation Validation**

To mature the algorithm, and to get ready for flight test, which is the ultimate testing, several simulations have been conducted in a ground flight simulator. In each simulation, the U.S and Swedish Air Force pilots evaluated different collision scenarios. The pilots evaluated the Auto ACAS in functionality, intended capability, and performance. The evaluated scenarios ranged from a close formation flight to air combat training maneuvers. In addition, the off-line simulation collision scenarios provided statistical data that can be used to predict the escape direction that the ACAS algorithm would choose when collisions become imminent. Piloted Aircraft Collision Scenario tested the validity of escape angle for both the two

aircraft collision case and multiple aircraft collision case. It also tested formation flight logic, and nuisance levels to the pilot at the activation of the escape maneuver and during the escape maneuver. Piloted/UAV Collision Scenarios tested whether or not UAV successfully gets out of the piloted aircraft's way to avoid the collision without interfering with the pilot's missions. Air Combat Scenarios tested the algorithm performance in dynamic situations, which are always difficult due to unpredictability. Rejoin & Formation Flight Scenarios tested the validity of cases when the algorithm suppresses the activation of escape maneuver to allow a pilot to rejoin for close formation and when the algorithm activates an escape maneuver to protect the pilot from a collision. Failure ACAS Scenarios tested the algorithm's capability for fail safe operation against various possible failures. Finally, real historical accident cases were reconstructed and simulated with ACAS on-board.

Of all the test cases simulated, Auto ACAS did not allow any collision, nor caused collisions. So the efforts were focused on improving the nuisance level to the pilots in the evaluation. Major issues in this regard were whether or not the escape direction selected by the algorithm was comfortable to the pilots, and if the escape maneuver initiation timing was appropriate. The nuisance level was higher in the earlier simulation, but improvements since then were made based on the pilots' comments. As a consequence, pilots' comment after the last simulation was complementary overall. Escape maneuvers that were apparently a nuisance to the pilots were improved, which leaves a few cases that are either no nuisance to some pilots or still somewhat a nuisance to others. This indicates the algorithm has been refined so as to leave only the gray area, and the decision is up to the pilots' subjective opinion.

Several historical accidental data were used to evaluate the capability of the algorithm during the simulation. It seemed that the algorithm was able to save the accident.

## **6. Conclusions**

The current state of the Automatic Air Collision Avoidance System algorithm development and its performance were discussed. The final algorithm evaluation in ground simulation showed that the algorithm performed at an acceptable level against collision avoidances, nuisance potentials, subsystem effects for manned and unmanned air vehicles. Currently, the algorithm is frozen for flight test integration, while refinement continues.

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